

USGS PLAN FOR WATER-RESOURCES SCIENCE IN THE PACIFIC ISLANDS REGION

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INTRODUCTION

This plan describes USGS Water Resources programs in Hawaii and other Pacific islands, and provides a rationale for USGS programs in hydrologic data collection and investigative work. The Hawaii District is part of the Western Region of the USGS. Other USGS offices working in Hawaii and the Pacific Islands include the [Pacific Island Ecosystems Research Center](#), [Hawaii Volcano Observatory](#), [Coastal and Marine Geology Program](#), and [National Mapping](#). These USGS offices work together to provide relevant, impartial, and high-quality scientific information to promote public safety and wise resource management.

The geographic domain of these investigations includes the islands in the State of Hawaii, the Commonwealth of the Northern Marianas, the Territories of Guam and American Samoa, the Federated States of Micronesia, the Republic of the Marshall Islands, and the Republic of Palau. These islands can generally be classified as either high islands (volcanic or limestone islands with an elevated land mass) or atoll islands (low-lying carbonate islands along the perimeter of a

coral atoll).

The main office of the Hawaii District is in Honolulu. Field offices are located on Kauai, Maui, Hawaii, and Saipan. The District operates a network of stations that collect information on streamflow, suspended sediment, lake and reservoir stage, ground-water level and salinity, rainfall, and evapotranspiration. The District also carries out interpretive studies on the quantity, quality, and dynamics of surface and ground water. For more information on the organization and activities of the District, go to <http://hi.water.usgs.gov/>. Work in the Hawaii District is funded by many cooperating agencies, as well as by federal funds allocated to the District.

Most islands contain water resources of significant economic, cultural, and ecologic importance. In many areas, ground water provides essentially all municipal and domestic water for expanding populations, while streams provide water supply for agriculture and important riparian and instream habitats for many threatened and endangered species. Hydrologic and climatic variability complicates the understanding and management of water resources. In addition, the physical, chemical, and aesthetic quality of receiving waters, such as estuaries, bays, and nearshore waters are important to both the ecology and the tourism-based economies of Hawaii and other Pacific islands. As island populations continue to grow, water resources are becoming more intensively developed, and in many areas the competition for resources is fierce. Consequently water-resource development has become an increasingly important component of political, economic, cultural, and environmental decisionmaking. Important water-related issues include:

- Long-term ground-water availability
- Quantity and variability of streamflow
- Water and sediment transport within watersheds
- Water-quality changes related to land use
- Climatic variability

All of these issues are relevant to the management of water resources in the State of Hawaii and also are relevant to many of the high islands in the Western and South Pacific. On the atolls of the Western Pacific, the absence of mountains and surface-water resources limits the issues of concern to long-term ground-water availability, water-quality changes related to land use, and climatic variability.

Past and present activities of the USGS and future actions directed at these issues are discussed in sections specific to the Hawaiian islands, other high islands in the Western and South Pacific, and coral atolls in the Western Pacific. For each issue, the following outline is used:

- Background—This section briefly presents the historical, social, and technical contexts of the issue, and describes why the issue is important to the Nation, the State of Hawaii, or other affiliated island groups.

- Current knowledge and USGS participation—This section describes the state of current knowledge regarding technical aspects of the issue, including the extent of available data and the level of understanding of hydrologic processes that affect the issue. Participation by the USGS in data collection and interpretation is outlined, as well as current contributions and approaches to advancing the state of hydrologic knowledge and understanding.
- Information needs and deficiencies—Some lack of information and/or lack of scientific understanding of the hydrologic and ecologic systems is usually at the heart of an issue. The types of hydrologic information and understanding that are currently lacking and that are most critical for resolving the issue are outlined and described in this section.

Each issue is described most completely in the section on the Hawaiian islands. Details specific to the other areas are discussed in the sections on the high islands of the Western and South Pacific, and atolls of the Western Pacific.

HAWAIIAN ISLANDS -- WATER ISSUES

The State of Hawaii has a total land area of about 6,400 square miles. The inhabited islands range in size from 70 (Niihau) to 4,000 (Hawaii) square miles. The island of Oahu, which has an area of roughly 600 square miles, is the capital and home to about two-thirds of the residents of the State. The State is divided into four counties with each major island being a separate county. The total population of the State is now about 1.2 million, and has grown from about 0.5 million in 1950. This increase in population has resulted in widespread changes in land use and an increase in the demand for freshwater.

Rainfall at various locations in the State ranges from about 15 to more than 400 inches annually. Watersheds on the windward sides of islands tend to have perennial streams sustained by ground-water discharge, whereas leeward watersheds typically have ephemeral streams. Watersheds are small and streamflow rises quickly during storms. Traditionally, streamflow was an integral part of the native culture and surface water was used to irrigate taro. Extensive diversion of surface water for commercial cultivation of sugarcane started in the late nineteenth century and still continues, although for other uses in addition to sugarcane. This diversion, along with the introduction of grazing mammals, has greatly changed the characteristics of many watersheds.

Most aquifers are unconfined. Variability in geologic settings, rock permeabilities, and recharge results in ground-water occurrence ranging from thin lenses of brackish water underlain by saltwater to vertically extensive freshwater bodies. In many areas, streams are incised below the water table and ground-water discharge is an important component of stream base flow. Ground water is the major source of potable water, but the extent and sustainability of this resource is unknown. Management of water resources is entrusted to the State Commission on Water Resource Management (CWRM).

In summary, the State has a large and growing population that is unevenly distributed on several small islands. Hydrologic processes are highly variable over short intervals of space and time,

and multiple demands for limited resources have reinforced the need for scientifically sound approaches to water management. Described below are activities of the USGS and a vision of additional work needed to further the scientific basis used to manage water resources.

Long-term ground-water availability

Background

Ground-water availability is a major water-resource issue in Hawaii. Ground water provides about 99 percent of Hawaii's domestic water and about 50 percent of all freshwater used in the State. Most ground water in Hawaii is developed in accessible areas, at low elevations, and near existing population centers. The potential for saltwater intrusion is high for many important sources of ground water in Hawaii. The long-term availability of ground water is dependent on the distribution and rates of ground-water pumping and on the depth of individual wells. Fresh ground water also is obtained from systems where water levels are tens to hundreds of feet above sea level. Although high water levels generally provide protection from saltwater intrusion, the long-term availability of water in such systems may be difficult to predict because of the geologic complexity.

In addition to its economic value, ground water is also ecologically and culturally important. Ground water sustains coastal springs and wetlands, supplies a component of freshwater to native Hawaiian fishponds, and in some areas of the State contributes to perennial streamflow. Streams and wetlands are habitat for endangered and native species.

Considerable competition exists in Hawaii for limited ground-water resources. Because ground-water development can affect (1) the quality of water pumped from existing wells, (2) stream, wetland, and coastal ecosystems, and (3) water availability for farmers that rely on ground water or base flow in streams, proposals for additional development are often met with opposition.

Regulation of ground-water development should consider, among other things, the hydrologic effects of proposed withdrawals. The method currently used to estimate sustainable yield, however, does not account for the spatial distributions of aquifer hydraulic properties, pumping, recharge, and discharge. Thus, the method cannot address the potential effects of proposed withdrawals on water levels and water quality near existing wells nor the reduction of ground-water discharge to streams, wetlands, and coastal springs. The use of numerical ground-water models and information from monitor wells will more accurately address the hydrologic effects of ground-water development in the most important aquifers in the State. Numerical models also can be used to address the issue of reduction of ground-water discharge to streams, wetlands, and coastal ecosystems.

Current knowledge and USGS participation

In Hawaii, the most important sources of ground water are freshwater-lens systems, which include a lens-shaped freshwater body, an intermediate transition zone of brackish water, and underlying saltwater. At high elevations, ground water may also be found associated with dikes,

perched water bodies, or where low permeability has led to a vertically extensive ground-water body.

- The USGS has developed numerical ground-water flow models to quantify the hydrologic effects of additional withdrawals and to address the issue of long-term availability of ground water in selected areas of the State. Studies have been done in areas where development is widespread and in areas where ground water has either not been developed or is minimally developed. Completed studies include: the central corridor of Oahu, which contains the most important aquifer of the State; North Kohala and the Kona area on the island of Hawaii; the Lihue Basin on Kauai; and the island of Molokai.
- Recent ground-water studies have identified a large region on Kauai where vertically extensive freshwater-lens systems exist. This region is characterized by high water levels, but the high water levels are not associated with dikes or perched aquifers. Information from test drilling, aquifer testing, hydrologic monitoring, and numerical modeling provide internally consistent evidence that indicate the high water levels are part of thick, fully saturated aquifers created by relatively large ground-water fluxes through low-permeability aquifers. A similar situation appears to exist in parts of the northeast area of West Maui.
- The USGS has estimated ground-water recharge for some areas of the State, including those areas where numerical flow models and new conceptual models of ground-water flow systems have been developed.
- Sustainable yield in Hawaii is calculated using an analytical model. The USGS recently completed a report comparing water levels calculated using a numerical ground-water flow model with those calculated using this analytical model. The report highlights some of the technical limitations of using an analytical model to estimate long-term ground-water availability.
- For the Iao aquifer on Maui, the USGS conducts a monitoring program to help in the assessment of the long-term availability of ground water. The USGS summarizes rainfall, ground-water levels, pumpage, and chloride concentration in water from pumped wells, and depth to, and thickness of, the transition zone between freshwater and saltwater. This aquifer is the largest on Maui and the second most important in the State.
- The USGS has used numerical models to estimate the reduction in discharge to coastal areas that may be caused by proposed ground-water withdrawals. These estimates have been made for southern Molokai, the wetlands in the Kaloko-Honokohau National Historical Park on the island of Hawaii, and streams and coastal waters near the Lihue Basin on Kauai.
- The USGS has been monitoring discharge at the Pearl Harbor Springs of southern Oahu for about 30 years to quantify the effects of ground-water withdrawals on spring discharge. Discharge from the springs maintains coastal wetlands and is used for watercress cultivation.
- Drilling of monitoring wells is done to provide opportunities for long-term data collection, geohydrologic exploration in new areas, and to enhance our conceptual understanding of

ground-water flow. Areas of exploration include the Lihue Basin on Kauai, the north shore and Pearl Harbor aquifer on Oahu, the Kualapuu area of Molokai and the Kula area of Maui, and several locations on the island of Hawaii.

Information needs and deficiencies

The following information needs and deficiencies related to the issue of long-term ground-water availability were identified:

- ***Improved recharge estimates***—Assessing long-term availability of ground water requires accurate estimates of ground-water recharge. Although recharge has been estimated for some areas, statewide recharge estimates are needed for effective management of ground-water quantity and quality.
- ***Numerical simulation of resource sustainability***—Appropriate management of the limited ground-water resources of the islands, for both average and drought conditions, requires development of predictive tools such as numerical ground-water flow models. New modeling codes allow for more detailed simulation of ground-water flow that considers the mixing of fresh and salt water within the aquifer. Such models, if constructed with accurate field data, can provide important insights into the effects of pumping and the long-term sustainability of ground-water resources.
- ***Improved monitoring of water levels***—A better spatial distribution of water-level monitoring is needed to improve the understanding of the ground-water flow systems in the State and to improve estimates of ground-water availability.
- ***Assessment of hydrologic and ecologic effects of ground-water development***—Ground-water withdrawals cause a reduction of discharge to streams, wetlands, and coastal ecosystems and possibly an increase in salinity of the water discharging to these ecosystems. In some areas of the State, the hydrologic effects of proposed withdrawals have been estimated using numerical ground-water flow models. However, the hydrologic effects of additional withdrawals are unknown for some of the State's important aquifers. Furthermore, the ecologic effect of reduced ground-water discharge to streams is poorly understood.
- ***Determination of the depth of ground-water flow systems***—An improved understanding of the depth of ground-water flow systems in some areas of the State is needed to refine conceptual and numerical models. For instance, the depth to which ground water flows in vertically extensive freshwater-lens systems and dike-impounded systems is poorly known.
- ***Evaluation of salinity data from deep monitor wells***—In some areas, there is heavy reliance on salinity-versus-depth profiles from deep monitor wells to regulate withdrawals. Because of possible borehole flow effects, however, salinity profiles from deep monitor wells may not accurately reflect salinity in the aquifer. Measurement of borehole flow is needed to evaluate the validity of salinity data from deep monitor wells

- ***Three-dimensional upconing analysis***—Long-term availability of ground water can be limited by saltwater intrusion problems such as upconing beneath production wells. Better estimates of dispersivity and vertical hydraulic conductivity are needed to improve the understanding of upconing in the different ground-water settings in Hawaii. These improved estimates can be used in a three-dimensional analysis of upconing using a numerical flow and transport model.
- ***Aquifer properties***—Many single-well aquifer tests have been conducted in Hawaii. However, much of the data have not been compiled or analyzed. Compilation and analysis of existing data can lead to an improved understanding of the flow systems in some areas of the State. Furthermore, multiple-well aquifer tests are needed to estimate aquifer-storage properties, which are needed to understand the transient effects of withdrawals.
- ***Hydrologic settings in poorly understood areas***—In some areas of the State, long-term ground-water availability is poorly known because the hydrologic setting is not well understood. In these areas, additional hydrologic and geologic information is needed to improve the understanding of the conceptual framework of the ground-water flow system.
- ***Capture zones of wells***—Estimates of the capture zones of production wells are needed to assess the potential for ground-water contamination at the wells. This information can have a bearing on the long-term availability of ground water from an area.

Quantity and variability of streamflow

Background

Streams currently provide about 50 percent of all freshwater used in the State. The largest use of streamflow has been for irrigation. Traditionally, streamflow was diverted for taro cultivation. Since the late 1800's and early 1900's, much of the water in the perennial streams of Hawaii has been diverted for large-scale sugarcane cultivation. The water is transported from the wetter, mountainous windward areas to the drier, flatter, leeward parts of the islands through networks of ditches and tunnels. At many sites, the diversion of streamflow is sufficient to take all dry-weather flow of the streams at the point of diversion.

The development of high-level ground-water resources in some settings can also reduce the base flow of streams by diverting the ground water away from gaining stream reaches. Consequently, assessments are needed of the amount and spatial input of ground water to streams, especially in areas undergoing ground-water development. In addition, estimates are needed of the magnitude of ground-water input to streams and the potential losses associated with any proposed ground-water developments.

The use of surface water in Hawaii is highly contentious because the economic need for agricultural and municipal water must be balanced against the cultural and environmental needs for the resource. There is a growing appreciation that the small watersheds in Hawaii are hydrologically sensitive and the associated aquatic ecosystems are fragile. Streams support

aquatic species found only in Hawaii. These species require sustained and variable streamflow conditions to survive. Also, surface water in Hawaii has been an integral part of the native culture, specifically for taro irrigation and subsistence harvesting of freshwater biota. Water in streams is also important for recreational and aesthetic purposes and its contribution to nearshore waters and ecosystems. Predicting the hydrologic and biologic effects of streamflow diversions or flow restorations will become increasingly important to decisionmakers.

In addition to the issues discussed above, which deal primarily with limited availability, excesses of streamflow can also be a significant cause for concern. In Hawaii most stream drainage basins are small and have steep slopes. As a result, flash floods that occur in response to short periods of intense precipitation are common in Hawaii. These floods pose significant threats to life and property. In addition to the safety issues associated with floods, runoff plays an important role in the life cycles of numerous aquatic species. Large fluxes of freshwater provide both the signal and pathway used to migrate upstream or out to the ocean, depending upon the species and the phase of its life cycle.

Current knowledge and USGS participation

Assessing the quantity and variability of streamflow in Hawaii is driven by the use of surface water for irrigation and drinking water, information for flood control and municipal planning, concern over watershed degradation, the instream needs of aquatic communities, and water rights of native peoples. Characterization and measurement of streamflow is central to understanding these issues. In general, streamflow information has been gathered at specific sites along selected streams using continuous-record stations. To supplement the continuous-record stations, selected data are collected at partial-record stations such as crest-stage gages and low-flow stations. Synoptic base-flow discharge measurements along a stream reach (seepage runs) also are used to intensively characterize flow along selected sections of streams.

The stream-gaging program in Hawaii has been only moderately successful in documenting the quantity and variability of streamflow. According to a 1994 analysis of the stream-gaging program in Hawaii, only 139 of 376 perennial streams in the State have been gaged. Only nine continuous-record gages have been operated on ephemeral streams in Hawaii. The USGS currently (2002) operates a network of 76 continuous-record and 104 crest-stage gages in Hawaii. These gages are funded by a variety of Federal, State, and County cooperators. Data collected at these gages are published in a series of annual data reports and are made available in electronic data bases. To date, the only statewide analysis of streamflow characteristics at gaging stations was published using data through 1979.

Data cannot reasonably be collected at all sites on all streams. Therefore, to understand streamflow quantity and variability, other techniques have been used. Seepage runs have been used to extrapolate low-flow characteristics compiled at continuous-record stations to many locations along a stream reach. Numerous seepage runs have been conducted in northeast Maui and in Waiahole Valley on Oahu. Another data extrapolation technique is the use of statistical regionalization methods to transfer data collected at gaging stations to locations where no data currently are available. A regional flood-frequency study was done for the island of Oahu in 1994. Although the most recent analysis of this type for the other Hawaiian islands was

published in 1972, the USGS is currently revising statewide estimates of flood magnitudes at different recurrence intervals.

A regional analysis to estimate median streamflows for the windward area of Oahu was done in 1992. That study was moderately successful, indicating that techniques currently used to transfer low-flow characteristics in Hawaii need further refinement.

Recent USGS efforts to expand our understanding of low-flow characteristics have been directed to: 1) defining the base-flow component of streamflow at selected gaging stations, 2) conducting seepage runs on selected streams, 3) utilizing the above information to assist in calibration of ground-water models and to demonstrate via the models the relation between surface water and ground water in the modeled area, and 4) presenting results of these efforts.

The USGS has been increasingly involved with the issue of surface-water diversions. A recent landmark case concerns the Waiahole Irrigation System, which collects water that would otherwise discharge to streams in windward Oahu. Numerous groups petitioned to have the water restored to the streams, and a decision called for part of the diverted water to be restored to the streams. The USGS was involved in this process from the beginning because of the role of the USGS as an impartial scientific agency. We have helped to evaluate how any reduction of irrigation water being transferred to leeward Oahu will affect the Pearl Harbor aquifer. More recently, the USGS has increased data-collection efforts in windward streams through additional gages, seepage runs, and low-flow partial-record sites.

The Waiahole case was only the first of what will likely be an ongoing process in Hawaii to reevaluate alternative and often-conflicting uses of streamflow. Similar issues are being raised involving diversion of Honokohau Stream in West Maui, the Lower Hamakua Ditch on the island of Hawaii, and the East Maui Irrigation System. The cultural, economic, and environmental consequences of these decisions will have major implications in Hawaii for many years to come. A report on the Honokohau system is currently undergoing review. To provide information regarding the Lower Hamakua Ditch issue, the USGS is using seepage runs and collecting other low-flow data to quantify the variability of base flow in Waipio Valley. The USGS is also starting a five-year study of stream characteristics and aquatic habitat for streams in East Maui that are affected by flow diversions. Information from this study should permit the establishment of technically based instream flow standards.

In terms of flood issues, the USGS recently completed a report that documented peak flows and geomorphic changes resulting from a large storm in November 2000 on the east coast of the island of Hawaii.

Information needs and deficiencies

The following information needs and deficiencies related to the issue of the quantity and variability of streamflow are:

- ***Analyses of existing streamflow data***—Statistical analyses of existing data are needed to summarize streamflow information for greater use by cooperators and the public. Data

summaries such as flow-duration curves, monthly and annual means, and low and high flow duration and frequency analyses are often required. In addition to the statistical summaries of data, interpretive efforts such as trend analyses are important to indicate possible changes in water availability over time. The most recent statistical summary of streamflow information in Hawaii used data through 1979. Since then no extensive trend analysis effort has been undertaken.

- ***Real-time distribution of streamflow data via the Internet***—Although the number of stations is increasing, at present only 19 of the 76 operational stream gages in Hawaii transmit data in near real-time. Real-time data are useful for flood warning, management of water systems, and operation of specialized data-collection programs. This network, as well as the data processing and Internet resources necessary to support it, needs to be expanded.
- ***Determination of discharge at stream mouths***—Most stream gages in Hawaii have been operated in upland areas where diversions were planned. Little is known of the total flux of freshwater to Hawaii's nearshore waters and the associated contaminant loads this flow transports.
- ***Flow quantification on ephemeral and intermittent streams***—Most continuous-record stream gages in Hawaii have been operated on perennial streams. As a result, little is known about the persistence of flow on ephemeral and intermittent streams and how much surface runoff takes place. These data would be useful in water budget and ground-water recharge studies and studies concerned with the attenuation of flood peaks along losing stream reaches.
- ***Spatial and temporal variability of streamflow***—One of the most significant problems related to the description of streamflow in Hawaii is the extreme variability that exists along stream reaches. Our data network has been oriented toward describing conditions at a given point on a stream and little has been done to evaluate techniques that could be used to extrapolate these point data to alternate locations along the stream, and estimate spatial variability at ungaged sites. These issues would be addressed by increased collection of data at low-flow partial record sites and seepage runs. The operation of paired gages along stream reaches also would help to address the issue of spatial variability. Interpretation of these data will require improved regionalization techniques (below).
- ***Determination of stream discharge at land-use boundaries***—In Hawaii, the headwaters of virtually every watershed are in forested, conservation areas, and lower sections of the watersheds are commonly in either agricultural or urban lands. Boundaries between the different land-use areas are often distinctive. Runoff data that is specific to the major land-use types is needed for use in developing best management plans for watersheds and identifying contaminant and sediment sources.
- ***Regionalization of streamflow characteristics***—Streamflow data cannot be collected at all of the locations where it is needed. Therefore alternative techniques for transferring streamflow characteristics from gaged to ungaged locations need to be investigated. Commonly used regionalization techniques include the use of hydrologic modeling and statistical regression

procedures. These techniques could be used to provide improved estimates of streamflow characteristics at ungaged locations in Hawaii.

- ***Ground-water/surface-water interactions***—Interim streamflow standards call for the maintenance of streamflows at their current levels. Prior to development of new ground-water sources, effects on streamflows need to be assessed. To make this determination there is a need to understand the nature of ground-water/surface-water interactions. Such analyses also serve to increase the understanding of the hydrology in a given area. This information is important to other areas of study including migration of contaminants in the hydrologic environment.
- ***Determination of biologically based instream flow standards***—Biologically based instream flow standards are needed to protect native aquatic communities. Instream flow is only one part of the larger stream riparian habitat issue, which includes riparian habitat, geomorphology, sediment, and all other physical features that influence aquatic life. Most concerns about native species focus on the types of habitat streams should be managed for and the practices within a watershed that will promote the sustainability of those habitats. There is a need for regional-scale habitat assessments and a better understanding of fluvial geomorphologic processes that affect them.
- ***Water-use data***—Diversions of water for both off-stream and near-stream uses are common in Hawaii. What is commonly unknown are the total numbers of diversion points, the quantities of water diverted, and the ultimate fate of diverted waters (does some part of the diverted water end up being returned to the stream?). The lack of streamflow-related water-use data can present a significant roadblock that prevents the development of accurate data to describe the quantity and variability of streamflow in Hawaii.

Erosion and sediment transport

Background

The landscapes of the Hawaiian islands are unusual in comparison to those of North America, indicating that processes of erosion and sediment transport in Hawaii may differ substantially from processes in other parts of the United States. These apparent differences are increasingly of practical importance, because relatively little information on erosion and sediment transport is available for Hawaiian watersheds. As a result, empirical models developed for the mainland United States are being used by land managers to assess erosion and evaluate alternative land-use and conservation practices. The applicability of empirical models developed for use on the mainland for to evaluate erosion in Hawaii has not been well established, particularly for the mountainous, forested areas managed as the State-designated conservation-use districts.

Soil erosion from agricultural and conservation lands have caused concerns for many years in Hawaii, partly because of perceived relations between soil erosion and decreased infiltration of rainfall to ground water in upland watersheds. An extensive system of Forest Reserves was established, beginning during the Monarchy and into the early Territorial period, with the

intention of protecting these watersheds.

Recently, the Clean Water Action Plan has renewed efforts to control erosion and reduce sediment loads. Sediment was identified as the primary nonpoint-source pollutant in the State, and sediment is now the focus of the Total Maximum Daily Load (TMDL) plans being formulated in Hawaii.

Erosion and sediment transport in Hawaiian watersheds are of concern because sediment causes or is related to the following adverse environmental and economic problems:

- Increased turbidity, reduced instream water quality, and impaired aquatic habitat
- Loss of agricultural soil productivity
- Damage to coral reefs due to “smothering” with deposited sediment, transport of adsorbed contaminants to coastal receiving waters, and aesthetic impairment of coastal waters important for resident and visitor recreation
- Reduced flood storage capacity in engineered flood-control structures and decreased efficiency in agricultural water-delivery systems

Although erosion and sediment transport are natural processes of landscape evolution, erosion rates in Hawaiian watersheds have been accelerated since settlement and development of the islands as a result of:

- Large-scale sugar and pineapple cultivation, as well as coffee and macadamia nuts, and more recently diversified agriculture
- Introduction of feral ungulates, including pigs, goats, sheep, and deer, that destroy native vegetation and disturb soils, particularly in the more remote areas of the islands
- Livestock grazing, which causes the same problems as feral ungulates, but which is commonly concentrated in lower and drier areas
- Introduction of invasive alien plants that offer less protection from soil erosion than native plants and increase the frequency of wildfires
- Military training, including live-fire exercises

The combination of destructive land-use practices, introduced plants and animals, and extreme variations in rainfall have created spectacular examples of accelerated erosion in Hawaii. The most extreme example is the island of Kahoolawe, which was used as a military firing range for many years. Other obvious examples can be found in the drier areas of the islands of Molokai and Lanai. Erosion has probably also been accelerated in wetter areas, but the more extensive forest cover in these areas makes the erosion less noticeable.

Increasingly, efforts are being made to restore forested watersheds in Hawaii to more natural conditions. Public agencies and private organizations and landowners are working together to eliminate exotic plants and grazing animals and to replant native trees. The expenditures of time, effort, and funds on such projects are motivated in part by the desire to reduce sediment loads for protection of aquatic habitat and coastal water quality. Several such efforts are currently underway, although little scientific guidance is available. In particular, the identification of the most significant source areas of contaminants would allow projects to focus on the areas where they will be most effective.

Current knowledge and USGS participation

Most of the information available on erosion and sediment transport in Hawaii has been collected on the island of Oahu. Landslides on Oahu have been studied, measured, and related to long-term landscape evolution. In addition, denudation rates have been calculated for some of the Kaneohe Bay watersheds. Suspended-sediment data have been collected at gaging stations in the central windward and leeward Koolau Range on Oahu by the USGS, primarily for studies related to construction of the H-3 freeway, and also at a few other locations. The USGS completed an investigation of sediment sources in the North Halawa Valley in 1992 that examined erosion by natural processes and erosion resulting from highway construction. Data for TMDLs are currently being collected by USEPA contractors in several watersheds.

Data on erosion from agricultural fields have been collected at locations throughout the islands by the Natural Resources Conservation Service (Dept. of Agriculture) and the University of Hawaii College of Tropical Agriculture and Human Resources. In addition, USGS data have been used in an islandwide study of watershed denudation emphasizing chemical weathering.

The unusually large 1980 Olokele landslide on the island of Kauai was studied by the USGS shortly after it occurred. More recently, sediment transport in the Hanalei River, also on Kauai, has been studied by researchers from the University of Hawaii.

Currently, the USGS has no sediment program in Hawaii. The last sediment station operated for the H-3 Highway network was discontinued at the end of the 1999 water year. Limited sediment data were collected as part of the Oahu NAWQA program, but no daily suspended-sediment stations were being operated. Determination of suspended sediment flux and delivery to coastal waters requires data from automatic samplers because the flashy nature of Hawaiian streams makes it unlikely that representative samples can be collected manually.

Information needs and deficiencies

Given the limited information available, the needs and deficiencies are understandably substantial. The most urgent regulatory needs are for information for the preparation of total maximum daily loads (TMDLs) for 111 water-quality limited segments identified by the State Department of Health. Overall, scientific information needs for the State are:

- ***Sediment loads in relation to land use***—For planning purposes, the State of Hawaii classifies land use into three types: urban, agricultural, and conservation, which includes

forest reserves in mountainous areas. Recent efforts to deal with nonpoint-source pollution have focused attention on the relative contributions of these three land-use types to sediment loads reaching impaired-quality water bodies. At present, little information is available to characterize the relative contributions of sediment from the three types of land use at the watershed scale.

- ***Relative importance of erosional processes, particularly the role of landslides and channel erosion***—Most erosion-control measures used in Hawaii are directed at surface runoff and sheet and rill erosion. However, landslides and erosion of channel banks may be significant contributors to sediment loads as well. Field data are needed to evaluate quantitatively the importance of erosional processes in delivering sediment to water-quality impaired segments of streams and coastal waters.
- ***Sediment-transport processes in ephemeral streams***—Severe erosion during the flood of November, 2000, on the island of Hawaii resulted from runoff in normally dry gulches. On the island of Molokai, sediment carried by ephemeral streams has a major effect on coastal waters. Data collection on ephemeral streams that are dry most of the time and rise to peak flows in a matter of minutes is challenging, and at present little information is available on the sediment-transport characteristics of Hawaii's ephemeral streams, even though large areas of Hawaii's land mass are drained by such streams.
- ***Effectiveness of best management practices and watershed restoration projects***—In the past decade, several large-scale efforts to protect and improve upland watersheds have been initiated in Hawaii. These projects are justified, in part, by their presumed effectiveness in moderating streamflow regimen and reducing erosion. However, few studies have been undertaken to monitor and demonstrate the effectiveness of such projects. Monitoring and analysis of results is needed to determine the most effective means of improving watershed quality.
- ***Sediment delivery to coral reefs***—Sediment from natural and disturbed watersheds is perceived as a cause of coral reef degradation in many parts of Hawaii. However, the amount of sediment that reaches the ocean is poorly known. More important, the extent to which land-use practices contribute to erosion and sediment delivery to coastal waters is not well quantified.
- ***Measurements of bedload transport***—Although fine sediment is most responsible for adverse effects on water quality, bedload is a problem for maintenance of flood-control channels in Hawaii. Bedload data are also needed to compare measured sediment loads to empirical models of total-sediment erosion such as the Universal Soil Loss Equation.
- ***Assessments of coarse-particle attrition as a source of fine sediment***—Owing to the extensive chemical weathering of primary minerals and the large amount of energy available for particle transport in Hawaiian streams, attrition of coarse particles during transport may be a significant source of fine sediment in Hawaii. However, little is known about the importance of this process for generating fine sediment and impairing the quality of receiving waters.

- ***Long-term records of sediment transport***—Such records are needed to better define erosion and sediment transport rates for Hawaiian watersheds in relation to geology, climate, vegetation, and land use.

Water-quality changes related to land use

Background

Major water-quality issues in Hawaii are related to protecting public drinking-water supplies and reducing the effects of land-use activities on surface and ground waters. Agriculture is a major industry in Hawaii and has had the widest effect on water quality, especially on the islands of Oahu and Maui. Nonpoint-source contamination of ground water is of particular concern to water-resource managers. The quality of surface water and its effect on the health of aquatic ecosystems is becoming increasingly important owing to several native and endemic aquatic organisms.

Significant water-quality changes are expected on the major Hawaiian islands as a result of rapid population growth and associated land-use changes. In particular, the island of Oahu has undergone significant urban and suburban growth over the past two decades. In addition, there has been a shift from large-scale plantation agriculture to small-scale diversified agriculture. These two factors, operating in concert, have led to both an increase in population density within urban and suburban areas and a change in type and amount of pesticides being applied. Continued growth within the urban area of Honolulu (and other towns) has increased stress on the environment and has resulted in degraded water quality. Urbanization affects water quality by changing land-cover characteristics from vegetation to pavement, increasing runoff to streams, and changing the types of contaminants carried by runoff. Replacement of single-crop agriculture with diversified agriculture will change the types and amount of herbicides and pesticides applied.

In general, the principal drinking-water aquifers in Hawaii are composed of highly permeable thin-bedded lava flows, and are highly susceptible to contamination. Although the aquifers are often deep, with a depth to water between 100 and 600 feet, contaminants have been found in more than 65 drinking-water wells. Of particular concern to health officials is the detection of ethylene dibromide (EDB), 1,2 dibromo-3-chloropropane (DBCP), 1,2-dichloropropane (DCP), chlordane, and dieldrin, all of which are carcinogens. Although these chemicals are no longer in use, an understanding of the factors controlling their fate and transport (and their degradation products) is needed by water-resource managers who would like to know when these contaminants will “wash-out” out of the ground-water flow systems.

With regard to surface-water quality, runoff from urban and agricultural areas has led to significant changes in the sediment loading and chemical characteristics of streams when compared to areas devoid of anthropogenic activity. An important concern in streams is the accumulation of toxins, such as metals and pesticides, and the associated effects on the aquatic community. Fish from Manoa Stream in urban Honolulu have some of the highest levels of mercury, lead, and pesticides in the Nation. To effectively assist land- and water-resource

managers with nonpoint-source contamination problems, we must increase our understanding of factors controlling relations among land-use practices and the physical and chemical loading in streams and delivery to estuaries, bays, and nearshore waters.

Finally, concerns over pathogens in surface and ground waters are increasing with improvements in microbial methodology, greater use of water resources, and heightened public awareness. Two specific concerns are apparent regarding pathogens. First, pathogens in runoff from urban areas and degraded watersheds may contaminate recreational fresh and nearshore waters. The issue is serious because of the high degree of recreational water use by residents and tourists. Standard USEPA methods and criteria for bacterial pathogens rely on indicator species that survive and multiply in subtropical environments, and thus do not necessarily indicate the presence of pathogens. The second issue regarding microbiology is the persistence of pathogens in reclaimed wastewater. Because many agricultural areas overlie potable aquifers, there is concern that the use of reclaimed wastewater may contaminate drinking water sources. Currently, nearly all wastewater in Hawaii is discharged through deep ocean outfalls. However, demand for water is increasing and the use of reclaimed wastewater for irrigation is rising.

Current knowledge and USGS participation

The factors controlling relations between land-use practices and water-quality conditions in Hawaii are either poorly understood or unknown. Historically, water-quality programs in the USGS have been mostly limited to site-specific data-collection activities, such as the NASQAN and Hydrologic Benchmark programs. A loss of funding has resulted in these programs being discontinued.

More recently, the USGS completed a water-quality monitoring project related to the construction of the H-3 Highway. The focus of this study was suspended-sediment loads in streams before, during, and after construction of the freeway. The USGS is currently engaged in a program to monitor the quality of storm-water runoff from the H-3 freeway, and the effect of this runoff on Halawa Stream.

The island of Oahu NAWQA study began in FY 1997 as the first large-scale water-quality program in the USGS. The program integrates monitoring surface- and ground-water quality with the study of aquatic ecosystems. The initial focus of this study is on the occurrence and distribution of water-quality conditions as it relates to natural factors and human activities. Preliminary findings indicate concentrations of organochlorine compounds in biota and sediment from Oahu streams are high compared with other regions of the Nation. In particular, concentrations of dieldrin and chlordane in fish tissue from urban sites are commonly an order of magnitude greater than guidelines for the protection of wildlife that consume fish. Work on the Oahu NAWQA study will cease after FY 2003 because water-quality issues in Hawaii were determined to be of low priority in addressing water-quality trends and processes for the Nation.

Information needs and deficiencies

While data-collection activities are necessary and important, there is a strong need for our programs to address water-quality issues from an island, or at least aquifer/watershed,

perspective. In addition, process-oriented studies are needed to enhance our understanding of water-quality changes related to land use. Better information on the following topics will improve our ability to protect drinking-water supplies and assess the effects of land-use activities on surface and ground waters:

- ***Estimates of sediment and nutrient loading in streams***—One hundred eleven water bodies in Hawaii have been listed for impaired water quality, mostly from suspended sediment and nutrients. Federal regulations require that a total maximum daily load (TMDL) be developed for each impaired water body. The cumulative costs to collect data for TMDL development across numerous water bodies could be very high. As a result, there is interest in alternatives to direct measurement of contaminant loads in multiple watersheds. One approach is to develop a land-use based numerical model that accurately represents the erosion or delivery of suspended sediment and nutrients and their loadings to receiving waters. Such a model could be used to evaluate loadings to impaired water bodies from specific land uses within watersheds. The model would also be useful in guiding the development and implementation of specific best management practices.
- ***Ground-water vulnerability assessments***—Several approaches are currently used in Hawaii to assess potential ground-water vulnerability from regional-scale applications of agrochemicals. In general, these assessments are based on soil, climatic, and chemical data that are extremely sparse and, therefore, contain considerable uncertainty. Model and data uncertainties must be incorporated into these assessments before GIS-generated ground-water vulnerability maps will be useful to regulatory decisionmaking. Furthermore, these models need to be statistically verified using water-quality data to provide a more technically defensible assessment. Unsaturated and saturated ground-water flow modeling coupled with age-dating techniques, such as CFC's, will be necessary to understand relations between land-use practices and ground-water quality, given the thick unsaturated zone in Hawaii.
- ***Transformation products of organic compounds***—The importance of transformation products of organic compounds, especially pesticides, is poorly understood or unknown. Monitoring studies of these transformation products and their parent compounds are needed in areas where parent compounds have been used extensively.
- ***Occurrence and distribution of pathogens***—Except for microorganisms commonly examined as indicators of fecal contamination, little is known about the presence of bacteria and viruses in ground and surface waters in Hawaii. Monitoring programs are based on non-pathogenic indicator species. The most commonly used of these species, such as enterococcus, fecal coliform, and *E. coli*, grow naturally in tropical soils and sediments, so most microbial data collected does not address either the issue of pathogen presence or contamination by wastewater. Although researchers at the University of Hawaii have found a more reliable indicator organism (*Clostridium perfringens*), additional information is needed on the environmental occurrence and distribution of pathogens.
- ***Effects of contaminants on aquatic communities***—Pesticides and trace elements are two groups of contaminants that are threats to aquatic communities. Land-use activities that increase the quantity of these contaminants reaching surface water are of particular concern

to aquatic communities owing to a wide range of potential toxicological effects. While agricultural activities are commonly linked to pesticide issues, it is important to recognize that urban activities in many areas, such as Honolulu, may contribute more pesticides to surface waters than agricultural activities. Likewise, urban activities are commonly linked to trace element issues, but in Hawaii natural sources of trace elements are significant owing to volcanic soils. Additional information on the effects of land-use activities on surface-water quality and aquatic communities are needed.

- ***Improved monitoring of watershed restoration programs***—Many of the watershed restoration efforts are in need of scientifically sound monitoring programs that will assist them in determining if changes in management practices are resulting in the desired outcome. There also is a need to incorporate various components of a biological system for monitoring either water or habitat quality to developing a better understanding of watershed structure and function in that biological systems are the integrators of watershed processes and are commonly the resource of interest to managers.

Climatic variability

Background

Because of their small size and limited storage of water, islands are particularly sensitive to variations in climate. Long-term changes in climate and short-term climatic variability pose challenges to water suppliers and resource managers. In Hawaii, severe droughts are associated with El Nino cycles, but may persist for years beyond El Nino events. During the most recent drought, many high-level springs experienced decreased flow or went dry; these springs supply domestic water that is important to some rural areas of Hawaii. Streamflow was significantly reduced in many parts of the state, affecting water supplies for domestic and irrigation uses. One of the most heavily used aquifers, the Iao aquifer on the island of Maui, experienced decreased water levels and increased chloride concentrations. However, many of the pumped aquifers in Hawaii appear to have had no trouble during this event, although evidence is mainly anecdotal. Overall, the climatic component of aquifer response to these decadal-scale events has not been investigated.

Over a longer time scale, there is a growing consensus that human activity is greatly accelerating the rate of climate change. Although the predictions are variable, many forecasts indicate that carbon dioxide in the atmosphere will double by 2050. Predicted consequences are a sea-level rise of about 1 foot, a 30 percent decrease in coral reef growth, and most important, increased climatic variability. This will cause both the frequency and intensity of extreme hydrologic events to increase. For coastal areas and small islands, saltwater encroachment and inundation will increase because of rising sea levels and increased storm activity.

Current knowledge and USGS participation

The effects of long-term changes in climate on the hydrology of the Hawaiian islands are largely speculative. The frequency of extreme events such as storms and droughts will likely increase.

Also, the combination of sea-level rise and decreased rates of reef growth will lead to increased coastal erosion that may affect some local water resources. Finally, it is possible there will be a long-term change in net rainfall. A long-term decrease in mean rainfall would have a serious effect on water resources. At the present time, the spatial resolution and system feedbacks of numerical climate models are not sufficient to predict the long-term effects of human activity on climate.

The USGS has produced maps of ground-water recharge for much of the State and is currently in the process of updating some of these maps using better methods and additional data. These recharge estimates are estimated from daily water budgets on the basis of long-term average data. The methods developed to produce the average recharge estimates could easily be incorporated into studies of specific time periods, such as during El Nino events, when rainfall, and hence recharge, is greatly reduced. The USGS data network has several long-term (more than 60 years) sites and is available for analysis of trends in surface and ground water related to both short- and long-term changes in rainfall.

The frequency of landslides is also likely to increase if the intensity of extreme storms rises. A joint project with the USGS Geologic Discipline several years ago was directed at mapping landslide areas on the island of Oahu and determining the causes of such landslides. Subsequent research by geologists has increased our understanding of landslide processes.

Information needs and deficiencies

Climatic variability and climate change should be imbedded in the design of all hydrologic projects. Most water-resource management strategies are designed for current, average, or historical climate regimes. These strategies may not accurately reflect actual future conditions and may fail when applied to systems stressed with increasing development and variable climatic factors. As a result, methods are needed to account for climate variability in developing short-term and long-term strategies related to water availability. The interaction of changes in hydrologic and biologic systems (for example, streamflow and native fish species migration) owing to climate variability is poorly understood or unknown. An increased understanding of the role of climate variability in ground-water levels, streamflow, and aquatic communities would provide important information on the temporal aspects of water use, water budgets, water availability, and biologically based instream flow standards.

WESTERN AND SOUTH PACIFIC HIGH ISLANDS -- WATER ISSUES

In addition to the State of Hawaii, the USGS also conducts work in the Territories of American Samoa and Guam, the Commonwealth of the Northern Mariana Islands (CNMI), the Federated States of Micronesia (FSM), and the Republic of Palau. The volcanic rocks in the high islands in these groups are older and of a different composition than those found in the Hawaiian islands. Carbonate platforms are also found along the coastal areas of some islands and are a major component of the land mass in the uplifted islands adjacent to the Marianas Trench (Guam and CNMI). Many of the islands receive nearly 100 inches or more of rain annually, and rainfall tends to be seasonal. El Nino events result in periodic but severe droughts throughout the region.

Several of the more populated islands have municipal water supply systems. Many rural systems rely on direct catchment of rain and shallow wells. All of the islands have rapidly growing populations. Population and economic growth during recent decades have greatly increased the demand for water on many islands.

American Samoa has been a U.S. territory since 1900. The current population is about 60,000 and the main island of Tutuila has an area of 53 square miles. The terrain is steep and heavily vegetated, and watersheds are small. The municipal water system is largely dependent on ground water.

Guam became a U.S. Territory in 1898 and has a population of about 130,000 and an area of 212 square miles. In the northern half of the island, limestone overlays volcanic rocks to depths of several hundred feet and extends below sea level. The limestone is heavily weathered, highly permeable, and exhibits many karst-like features. There is very little direct surface-water runoff, and nearly all public supply comes from ground water. In the southern half of Guam, weathered volcanic rocks dominate the land surface. The low permeability of the volcanic rocks has inhibited the development of ground-water resources. The Fena Reservoir (constructed and maintained by the U.S. Navy) is the largest source of water in the southern part of the island.

The CNMI comprises three major islands: Saipan (48 square miles), Tinian (41 square miles), and Rota (33 square miles), and thirteen smaller islands. Most of the population of about 70,000 lives on Saipan. The major islands consist of a volcanic core that is mostly below sea level and overlain by limestone. There is very little direct runoff of surface water. Fresh ground-water lenses exist on all three islands and high-level ground water occurs on Saipan and Rota. Drinking water on the three islands is obtained almost exclusively from ground water as it discharges at springs or from wells.

The Federated States of Micronesia includes the island groups of Chuuk, Kosrae, Yap, and Pohnpei. These island groups, together with the Republic of Palau, contain a large number of islands that range from low-lying atolls to volcanic high islands. The population is increasingly concentrated on a few of the larger islands. Watersheds are small and streams are flashy. Water-supply systems rely on diversions of surface water and wells, although the generally low permeability of the volcanic material limits the production from individual wells.

Long-term ground-water availability

Background

Ground-water availability is a major concern on many of the high islands in the Western and South Pacific. Ground water is the major source of municipal water on the islands of the CNMI and in northern Guam. For instance, the CNMI is nearly completely dependent on ground water for drinking water, and about 80 percent of Guam's residents rely on ground water from the highly permeable limestone in the northern part of the island.

Assessing the long-term availability of ground water for some islands is made difficult by the

complex geology and limited hydrologic data. Furthermore, on the islands of Guam, Saipan, and Tinian, developed freshwater lenses are much thinner than those found in Hawaii and are therefore more prone to upconing and high salinity problems caused by short-term climate variability. On islands experiencing rapid population growth, such as Saipan, increased water demand can exacerbate the problems of limited ground-water resources. Thus, identifying appropriate development and management strategies for long-term sustainability of the ground-water resources is a critical issue among the high islands in the Western and South Pacific.

Current knowledge and USGS participation

Current knowledge and USGS participation among the high islands in the Western and South Pacific are briefly summarized below:

- **Guam**—The Barrigada and Mariana Limestones are the two primary aquifers in northern Guam. In 1978, these aquifers, commonly called the Northern Guam Lens aquifer, were designated by the USEPA as a “sole source aquifer”. Ground water in Guam is managed with a system similar to that currently used in Hawaii; the estimates of sustainable yield and the way in which aquifers are delineated are not scientifically rigorous. Consequently, it is possible that ground-water resources are not being developed with the best information to ensure long-term availability. To improve the quality of data collected, the USGS recently renovated several monitoring wells in the northern Guam lens. The USGS program on Guam has been augmented by increased cooperation with the Water and Environmental Research Institute (WERI) at the University of Guam.
- **Saipan**—Most water on Saipan is obtained from freshwater-lens systems having a water table that is generally less than 2 feet above sea level. As a result, the availability of freshwater is highly dependent on the distribution and rates of ground-water pumping and on well depths. Additional ground water is available in the interior of the island where faulting and geologic structure results in high water levels. Considerable exploration is required to understand the extent and availability of freshwater from these bodies with high water levels.

On Saipan, the existing demand for municipal water is not met. Some areas of Saipan are not connected to the water system due to a lack of available water, and water use in other areas may be restricted to certain hours. Periodic drought during El Nino events exacerbates this problem. During the period of rapid growth on Saipan, the increased demand for water was met by over-pumping existing well fields and, consequently, the average chloride concentration of domestic water on Saipan rose above 1,000 ppm. Chloride concentrations averaged about 1,200 ppm during the 1998 drought.

Since 1988, the USGS has monitored ground-water levels, pumping distribution and rates, and chloride concentrations at existing well fields on Saipan. The cooperative effort has included a program of test drilling throughout the island to find new sources of water, and construction of a preliminary ground-water model of the freshwater-lens system in the southern peninsula of the island.

In 1999, the USGS began a two-year study of water resources on Saipan that includes: (1) aquifer tests at exploratory wells in the central highlands of Saipan, (2) quarterly sampling of monitor wells that penetrate through the transition zone between freshwater and saltwater, (3) water-level and pumpage data collection from wells in the southern peninsula on a continuing basis and utilization of this information to update the existing ground-water flow model, and (4) development of a numeric ground-water flow model for Saipan to assist in management of the aquifer during average conditions and to better understand and predict the aquifer's response to drought.

- ***Tinian***—The surface geology of Tinian is permeable limestone, and has a single low-lying freshwater-lens system with water levels generally less than 2 feet above sea level. Until recently, a single infiltration gallery well supplied all of the domestic demand for water on Tinian (about one million gallons per day). The chloride concentration of municipal water averages about 180 ppm, but approached 250 ppm during the 1998 drought. A new infiltration gallery has recently been installed and now provides most drinking water for the island. Water for agriculture is pumped from another well.

Further development of freshwater on Tinian will depend on the distribution and rates of ground-water pumping and on well depths. A recently completed USGS project on Tinian resulted in the emplacement of a hydrologic network and the definition of the extent and thickness of the freshwater lens. As part of the completed project, 22 exploratory wells were drilled and 18 wells drilled in 1944-45 by the U.S. military were rehabilitated. A preliminary model of the ground-water system was also constructed to better understand the aquifer's response to drought.

- ***Rota***—Nearly the entire water supply for the island of Rota is derived from two springs located on the south side of the island. The island has a series of limestone plateaus that are underlain by volcanic rock. The springs issue from the base of the highest plateau on the island at an altitude of several hundred feet above sea level. Five nearby perennial streams also form at the contact and flow over volcanic rock to the ocean. Six wells were drilled in the limestone to tap the fresh ground-water lens, but two of these have been shut down because the water was brackish. There is little information on the discharge characteristics of the springs and no information on the discharge characteristics of the streams. Springflow decreased during the 1998 El Nino drought to the point that water service was limited from April to August to daylight hours only. There is a need to begin to understand the geohydrologic setting of Rota and to begin to quantify its water resources.

A recent two-year cooperative effort on Rota was designed to address the water-supply problem on Rota and to obtain basic information on the island's water resources. The effort involved: (1) water-level, chloride analysis, and aquifer tests of five exploratory wells, (2) chemical analysis of the water from the wells and the two springs, (3) discharge measurements from the largest spring and three partial-record streamflow sites, and (4) rainfall data collection at one site gage.

- ***Tutuila***—On the island of Tutuila (American Samoa), the municipal water system draws from about 60 wells. The volcanic rock comprising most of the island has a low permeability,

and the water level in many wells is drawn below sea level at moderate pumping rates. The USGS has compiled annual summaries of ground-water data and recently completed a hydrologic atlas of Tutuila. Because calculation of ground-water recharge for Tutuila is hindered by the lack of evapotranspiration data, stations are being operated at several locations on the island to collect data that will aid in the construction of a water budget.

- ***Other high islands***—Ground water is utilized to varying degrees on several of the high islands in the FSM and Republic of Palau. At present, the USGS does not have ongoing programs directly related to ground water in these countries, although we have assisted with resource assessments in the past.

Information needs and deficiencies

The following information needs and deficiencies related to the issue of long-term ground-water availability on the high islands of the Western and South Pacific were identified:

- ***Numerical ground-water flow models***—Appropriate management of the limited ground-water resources of the high islands, for both average and drought conditions, requires development of predictive tools such as numerical ground-water flow models. Development of numerical models, however, requires the additional information listed below.
- ***GIS database viewer to facilitate hydrologic analyses***—A simple GIS-based system to readily view hydrologic data would greatly facilitate analyses of ground-water conditions, identification of data gaps, and development of numerical ground-water models. Furthermore, with GIS database viewers, cooperators are given the ability to quickly check on the status of their ground-water resources.
- ***Water budgets***—Estimates of ground-water recharge from water budgets are needed as input to numerical ground-water flow models. For many areas, data related to the components of the hydrologic budget are lacking. For some islands, the distributions of rainfall and evapotranspiration are poorly known. Estimates of runoff are also lacking for many areas.
- ***Aquifer properties***—Estimates of the hydraulic characteristics of aquifers are needed to improve our understanding of the conceptual framework of the ground-water flow systems.
- ***Water levels and transition zone information***—On most islands, improved distributions of water levels are necessary to improve our understanding of the ground-water flow systems. On some islands, such as Tutuila, information related to the depth and thickness of the transition zone is lacking. As in Hawaii, the effects of borehole flow on salinity profiles from open boreholes of deep monitor wells needs to be evaluated.

Quantity and variability of streamflow

Background

As in Hawaii, perennial streams in the high islands of the Western and South Pacific are sustained by ground-water discharge. At high elevations, ground water may discharge either from dikes, perched water bodies, or where low permeability has led to a vertically extensive ground-water body. In the latter case important springs on some islands are located at the contact between low-permeability volcanic rock and overlying highly permeable limestone that effectively limits the development of stream channels to areas where surficial geology is dominated by volcanic rocks.

Surface water is used for drinking-water supply extensively in some areas. Surface-water sources, however, are more vulnerable than ground-water sources to climatic variations such as the El Nino-related droughts. Increasingly, information is needed on surface-water availability during prolonged dry periods. Increases in population, such as on Saipan, or shifts in population, such as the planned relocation of the national capital of Palau, also create a need for streamflow information for water-resource planning.

Increased use of surface-water resources affects instream flows needed to support endemic and native aquatic communities. The aquatic communities of the Western and South Pacific islands are similar to those of Hawaii; however, the number of species is greater than in Hawaii. Information on streamflow in relation to aquatic habitat is needed to avoid adverse effects on aquatic flora and fauna.

Flooding is a concern on the high islands. Micronesia and Samoa are periodically affected by cyclonic storms that deliver large amounts of rainfall in short periods of time, as evidenced by the record peak-flows resulting from Typhoon Chata'an in Guam. Flooding is a frequent result, and as in Hawaii and on the mainland, floods endanger lives and property. Information on flood magnitudes and frequencies is needed for planning purposes.

Current knowledge and USGS participation

The USGS began monitoring streams in the high islands of the Western and South Pacific shortly after the end of the World War II. The stream-gaging program peaked in 1982, when 43 gages were operated on the islands of Guam, Saipan, Palau, Yap, Pohnpei, Kosrae, Chuuk, and Samoa. The program declined to 14 gages in Guam, Palau, and Samoa by 1997. Presently, 20 continuous-record streamflow gages are operated by the USGS in Guam, Rota, Palau, and American Samoa.

The USGS has completed several reports compiling streamflow data and analyzing rainfall-runoff relations, flow-duration curves, high-flow frequency curves, and low-flow frequency curves. The reports also compare streamflow at partial-record stations with streamflow at continuous-record stations. A recently completed project on American Samoa used existing data from 11 continuous-record and 75 low-flow partial-record gages to regionalize low and peak flows for 120 watersheds. Aside from these efforts, however, there have been no detailed

analyses of the historical data to determine streamflow characteristics, and nothing has been done to estimate streamflow quantities and variability at ungaged locations in other high islands.

On Guam the USGS has an ongoing program that uses a watershed rainfall-runoff model to predict monthly streamflow at three of the active gages on a monthly basis. The predicted streamflows are then used in a mass-balance model to predict water levels and storage in the Fena Reservoir. Data from 3 rain gages and 3 surface-water stations is used in conjunction with historic conditions and climate forecasts to simulate varying levels of water use on storage in the reservoir. This program has greatly aided management of water resources in southern Guam, especially during extended dry periods.

Information needs and deficiencies

The most glaring deficiency in the existing knowledge of streamflow in the high islands of the Western and South Pacific is the lack of published streamflow data for USGS gaging stations since 1991. The USGS is making progress on the unpublished records, but until the backlog is eliminated our ability to analyze and interpret surface-water data will be limited.

Other information needs and deficiencies include:

- ***Ground-water/surface-water interactions***—Although a limited number of seepage runs have been done in the high islands, little is known concerning the relations between ground water and streamflow.
- ***Long-term streamflow and rainfall data***—Unlike Hawaii, we have not operated any gages in the high islands for longer than 50 years. Even after the records backlog is eliminated, an effort will be needed to keep long-term gages operating to assess cyclical climate trends and land-use changes.
- ***Magnitude and frequency of floods***—With the exception of American Samoa, no recent flood-frequency analyses have been done for the high islands. The USGS is summarizing peak flows and the recurrence interval of flows caused on Guam by Typhoon Chata'an. This information could provide the foundation for regional flood-frequency analysis for southern Guam.
- ***Flood magnitudes and frequencies***—Flash flooding can be a pervasive problem in some areas. Improved estimates of flood magnitudes and frequencies are required at both gaged and ungaged locations to assist emergency management, planning, and public works agencies. With the exception of Samoa, no recent flood frequency analysis has been done for these islands.
- ***Stream ecology in relation to streamflow***—Little is known about the effects of varying levels of streamflow on aquatic organisms and community structure. The aquatic ecology of these islands has been minimally addressed, although many species are endemic to specific islands or island groups.

Erosion and sediment transport

Background

Concerns with erosion and sediment transport in the high islands of the Western and South Pacific are mostly related to effects on coral reefs and offshore receiving waters. Impairment of coastal water quality affects fisheries as well as recreational uses by residents and visitors. Increasingly, effects of sediment loads on public water supply are also being considered as limited ground-water resources are fully exploited and surface-water sources are considered for development.

Sedimentation is gaining attention on southern Guam because the stream water may be used to supplement municipal water from the wells in northern Guam. Fena Reservoir supplies part of Guam's municipal water. Sedimentation of this reservoir is a concern because its storage capacity is reduced by sediment deposition. This problem was exacerbated by a large influx of sediment caused by Typhoon Chata'an.

On Babelthuap (Babeldaob) Island in Palau, a major highway construction project is planned. Highway construction could result in dramatically increased stream sediment delivery to coastal waters.

In American Samoa, the local Environmental Protection Agency is interested in determining the importance of various land-use practices on sediment loads. Although most of the main island of Tutuila is forested, small-scale farms along streams may add to sediment loads generated by bank erosion.

Current knowledge and USGS participation

Sediment information for the high islands in Western and South Pacific islands is restricted to Guam. The USGS operated three sediment gages on southern Guam streams for a short period in the 1980's; three sediment samplers were also added to the stream gage network in 2000.

The USGS conducted two of the three surveys of Fena Reservoir following its construction in 1949, and has discussed renewed monitoring of Fena Reservoir following Typhoon Chata'an.

The University of Guam has conducted erosion plot studies in southern Guam, and cooperated with the USGS on a short-term study of erosion processes and sediment sources in the La Sa Fua watershed in Southern Guam.

In Palau, the USGS is assisting the national government in operation of suspended sediment samplers to assess the effects of highway construction on water quality

Information needs and deficiencies

The following needs related to erosion and sediment information have been identified for the high islands of Western and South Pacific:

- ***Effects of wildfires on soil erosion and badlands development***—Extensive dry-season wildfires are common in the uplands of southern Guam and several other islands. Wildfires may contribute to soil erosion and development of unvegetated scars known as badlands, but little is known about the effects of fire on soil detachment and transport.
- ***Updated Fena Reservoir storage capacity survey***—The last bathymetric survey of Fena Reservoir, a major municipal water source on Guam, was in 1990. Several large storms, including Typhoon Chata'an, have affected the island in the past 12 years, and erosion and sediment transport have likely diminished reservoir storage capacity. A new bathymetric survey and analysis of sediment quality in the reservoir would provide information needed to plan dredging, erosion control efforts, and pump relocation.
- ***Sediment delivery to coral reefs***—Sediment from natural and disturbed watersheds is perceived as a cause of coral reef degradation in many parts of Micronesia. However, the amount of sediment that reaches the ocean is poorly known. More important, the extent to which land-use practices contribute to erosion and sediment delivery to coastal waters is not well quantified.
- ***Sediment “fingerprints” for assessing sediment sources***—Initial efforts to use Cs-137 to differentiate sediment eroded from badlands and grasslands were encouraging. Further work could be done to test the usefulness of Cs-137 and other sediment tracers (“fingerprints”) in quantifying erosion from various potential sources.
- ***Relative magnitude of bedload transport***—Some suspended-sediment data have been collected on Guam, but except for reservoir sedimentation surveys no measurements of bedload transport have been made.
- ***Effects of coarse-particle attrition on size distribution of sediment loads***—Owing to the extensive chemical weathering of primary minerals and the large amount of energy available for particle transport in Hawaiian streams, attrition of coarse particles during transport may be a significant source of fine sediment in Hawaii. However, little is known about the importance of this process for generating fine sediment and impairing the quality of receiving waters.

Water-quality changes related to land use

Background

The major water-quality issues in the high islands of the Western and South Pacific are related to protecting public drinking water supplies and reducing the effects of land-use activities on surface and ground waters. Nonpoint-source contamination of ground water is of particular concern to water-resource managers. The quality of surface water and its effect on the health of aquatic ecosystems is becoming increasingly important on islands with significant surface-water resources.

The islands of Guam and Saipan have undergone significant population growth and associated land-use changes over the last two decades. The effects of past, present, and future land-use practices on ground-water quality is a major concern because most of the public water supplies on these islands are derived from surficial limestone aquifers that are highly susceptible to contamination. Fertilizers, pesticides, and solvents associated with urban, military, and agricultural land-use activities have the potential to contaminate ground water. Current monitoring by local agencies indicates that concentrations of all constituents are less than the maximum contaminant levels defined by the USEPA. However, the constituents being monitored do not include many of the pesticides being used.

Ground water from a USEPA-designed “sole source aquifer” provides about 80 percent of Guam’s drinking water. Potential sources of contamination to this aquifer include urban and agricultural areas as well as military installations, which have a wide variety of waste-disposal areas, including active and inactive landfills, sludge and chemical disposal pits, and petroleum disposal areas. Another source of potential contaminants is the Ordot Landfill, which is on the USEPA National Priorities List of hazardous-waste sites. Carbon tetrachloride, TCE, PCE, DBCP, EDB, chlordane, and dieldrin are among the contaminants detected at this site.

Nearly all of Saipan’s 60,000 residents rely on ground water developed from highly permeable limestone aquifers. Saipan has also undergone rapid urban development in recent years, including the construction of new industrial centers, homes, and golf courses. In addition, there has been a renewed interest in agricultural activities because of the high prices of imported fruits and vegetables. With increased urban and agricultural land use, the potential for fertilizers and pesticides to contaminate ground-water supplies will increase. Land-use planning, which is relatively new to this island, is beginning to focus on water-quality concerns.

Current knowledge and USGS participation

The factors controlling relations between land-use practices and water-quality conditions in the high islands of the Western and South Pacific are either poorly understood or unknown. To date, USGS water-quality programs have been limited to site-specific data-collection activities on the islands of Guam, Saipan, Tinian, and Pohnpei, and main islands of Chuuk, Palau, and Yap. While data-collection activities are necessary, and indeed an important component of the USGS program, there is a strong need for our programs to address water-quality issues from an island or at least aquifer/watershed-perspective. In addition, there is a need to develop process-oriented studies to enhance the understanding of water-quality changes related to land use.

Information needs and deficiencies

Better information on the following topics will improve the ability to protect drinking water supplies and assess the health of aquatic ecosystems:

- ***Occurrence and distribution of water-quality conditions***—There is a need to increase the understanding of water-quality conditions in the high islands of the Western and South Pacific. In particular, occurrence and distribution studies similar to those conducted as part the NAWQA program are needed to describe relations among natural factors, human

activities, and water-quality conditions. These studies would provide some of the information needed by water-resource managers to implement effective water-quality management actions and evaluate long-term changes in water quality.

- ***Ground-water vulnerability assessments***—Ground-water vulnerability assessments that show areas of greatest potential for ground-water contamination on the basis of hydrogeologic and anthropogenic factors are needed to protect drinking-water supplies on the islands of Guam and Saipan. Several approaches are available to assess the vulnerability of ground water to contamination. However, these assessments are based on soil, climatic, and chemical data that are extremely sparse and, therefore, contain considerable uncertainty. Model and data uncertainties must be incorporated into these assessments before GIS-generated ground-water vulnerability maps will be useful to regulatory decisionmaking. Furthermore, these models need to be statistically verified using water-quality data to provide a more technically defensible assessment.
- ***Transformation products of organic compounds***—The importance of transformation products of organic compounds, especially pesticides, is poorly understood or unknown. Monitoring studies of these transformation products and their parent compounds are needed in areas where parent compounds have been used extensively.
- ***Occurrence and distribution of pathogens***—Except for microorganisms commonly examined as indicators of fecal contamination, little is known about the presence of bacteria and viruses in ground and surface water. Monitoring is based on non-pathogenic indicator species that grow naturally in tropical soils and sediments. As a result, existing microbial data may not address either the issue of pathogen presence or contamination by wastewater, and additional information is needed on the environmental occurrence and distribution of pathogens.
- ***Determination of biologically based instream flows***—A critical need in protecting native aquatic communities is the determination of biologically based instream flow standards. Many concerns about native species focus on the types of habitat needed, and the practices within a watershed that will promote the sustainability of those habitats. There is a need for regional-scale habitat assessments and a better understanding of fluvial geomorphologic processes that affect them.
- ***Effects of contaminants on aquatic communities***—Pesticides and trace elements are two groups of contaminants that are threats to aquatic communities. Land-use activities that increase the quantity of these contaminants reaching surface water are of particular concern to aquatic communities owing to a wide range of potential toxicological effects. While agricultural activities are commonly linked to pesticide issues, urban and military activities in some areas may contribute more pesticides to surface waters than agricultural activities. Additional information on the effects of land-use activities on surface-water quality and aquatic communities are needed.
- ***Improved monitoring of watershed restoration programs***—Many of the watershed restoration efforts being undertaken by various Federal, State, and local agencies and private

organizations are in need of scientifically sound monitoring programs that will assist them in determining if changes in management practices are resulting in the desired outcome. There also is a need to incorporate various components of a biological system for monitoring either water or habitat in that biological systems are the integrators of watershed processes and are commonly the resource of interest to managers.

Climatic variability

Background

The small islands of the region are particularly sensitive to variations in climate. Compared to Hawaii, resources in these islands tend to be smaller and long-term changes in climate and short-term climatic variability pose challenges to water suppliers and resource managers. In most areas, rainfall is seasonal and El Nino conditions result in severe drought. Long-term climate change is also likely to result in sea-level rise, decreased coral reef growth, and most important, increased climatic variability. This will cause both the frequency and intensity of extreme hydrologic events to increase. For coastal areas and small islands there will also be an increase in saltwater encroachment and inundation because of rising sea levels and increased storm activity.

Current knowledge and USGS participation

The Fena Reservoir supplies most of the municipal water in southern Guam. Rainfall is highly seasonal, and the water supply is strongly affected by periodic droughts. The USGS assists in water management by using a rainfall-runoff model to predict reservoir storage on the basis of various rainfall forecasts. Both the rainfall-runoff and reservoir storage models are currently being revised.

The USGS has modified a ground-water flow models for the island of Tinian to simulate the effect of a sustained drought on aquifer recharge, ground-water salinity, and water availability. Work is in progress for similar simulations on a ground water model for the island of Saipan.

The USGS recently installed a discharge gage on a spring, the only water-supply source on Rota, to observe the hydrologic response to climate. The spring discharges water from a high-altitude aquifer and the flow is highly dependent on rainfall variability.

Information needs and deficiencies

As in Hawaii, most water-resource management strategies are designed for current, average, or historical climate regimes. These strategies may not accurately reflect actual future conditions and have a high probability of failure, especially when applied to presently stressed systems with increasing development. As a result, methods are needed to account for climate variability in developing short-term and long-term strategies related to water availability. The interaction of changes in hydrologic and biologic systems (for example, streamflow and native fish species migration) owing to climate variability is poorly understood or unknown. An increased understanding of the role of climate variability in ground-water levels, streamflow, and aquatic

communities would provide important information on the temporal aspects of water use, water budgets, water availability, and instream flow needed to maintain viable aquatic habitats.

WESTERN PACIFIC ATOLLS -- WATER ISSUES

More than 100 remote atolls containing about 2,000 separate islands are scattered in the Western Pacific. Most of these atolls are in the Republic of the Marshall Islands and the Federated States of Micronesia. Growing populations are creating demands that may exceed limited water supplies, especially on the smaller islands. The single most important hydrologic issue on the atolls is long-term ground-water availability. Water-quality changes related to land use is an issue that may potentially emerge, but is presently not a consideration of local authorities.

Atolls are sub-circular reefs that enclose a lagoon. Many small islands, commonly with an area of less than one square mile, are scattered along the surface of the reef structure. The islands are composed primarily of unconsolidated sediments and are readily infiltrated by recharge from rainfall. Rainfall typically averages more than 100 inches per year, and there is little or no surface runoff. If the infiltration from rainfall is sufficiently great, a lens-shaped fresh ground-water body forms. The distribution of fresh ground water primarily is controlled by the size and shape of the island and by variations in the hydraulic characteristics of the aquifer materials. Large, circular islands generally have large freshwater lenses. Small elongate islands promote mixing of freshwater with saltwater, and are associated with thin freshwater lenses and thick transition zones. The thickest part of the freshwater lens commonly is found in the fine-grained sediments on the lagoon side of islands.

Most communities on atoll islands rely almost entirely on rainwater catchment systems for drinking-water supply. Water rationing is required during periods of normal rainfall, and extended dry periods and droughts cause more severe water-supply problems. The failure of individual rainwater catchment systems during the dry season often is the result of inefficient catchment and undersized storage facilities.

Only two of the atolls, both in the Republic of the Marshall Islands, are developed with centralized water-supply systems, air and vehicular transportation, and electrical infrastructure. These atolls are Kwajalein, which has a U.S. military installation, and Majuro the capital of the Marshall Islands. On these atolls, centralized water-supply systems have been developed using large-scale rainwater catchment systems in combination with ground-water resources.

Long-term ground-water availability

Background

Ground-water availability is a major concern to atoll communities for public water supply as well as for taro cultivation. On the more developed atolls of Kwajalein and Majuro, ground water supplies about 30 percent of the public water-supply needs. On less-developed atolls, ground water from hand-dug wells is used mainly for washing purposes and not for drinking. Ground

water is the only source of water during persistent droughts.

On most atolls, conjunctive use of rain catchments and ground water is necessary. A major problem for atoll communities is that atolls are much more climate-sensitive than high islands because the small storage capacity of both catchment and ground-water resources renders water supplies highly susceptible to short-term climatic variations. The geographic isolation of atolls compounds the problem because alternative water sources are not readily available.

Ground-water resources have been used to help mitigate drought-related disasters on some atolls, such as Majuro and Kwajalein in the Marshall Islands. Unfortunately, the importance of ground-water development, monitoring, and management is not always recognized except during drought crises.

Current knowledge and USGS participation

Over the last 15 years, the USGS has made ground-water resource appraisals in the two westernized atolls, and four less developed atolls (Mwoakilloa, Pingelap, Sapwuahfik, and Ulithi, in the Federated States of Micronesia). As a result of these appraisals, conceptual and numerical models have been developed that describe the occurrence and movement of ground water on atoll islands. These models were developed using data from a network of multi-level monitoring wells installed in eight of the larger islands. The monitoring wells define the thickness and areal extent of freshwater in each island. Most of these appraisals, except for that of Kwajalein, were made prior to any substantial ground-water development. Ongoing monitoring programs, which are needed to assess long-term ground-water availability, have been difficult to maintain in many locales.

- **Majuro**—At Majuro Atoll, water shortages were severe during the 1998 El Nino drought. In March 1998, the centralized water-supply system, which serves more than 25,000 people, was able to provide water for only 12 hours once every two weeks. Without rainfall, the storage facilities were refilled at a rate of 100,000 gallons per day with ground water pumped from a freshwater lens located at the western end of the atoll. Although the condition of the freshwater lens was not known, the municipal water agency had plans to rehabilitate some of the existing wells in order to increase water production from about 150,000 gallons per day to about 275,000 gallons per day. The USGS assisted in relief efforts by installing a network of monitoring wells to determine the thickness and areal extent of the freshwater lens. Local residents had resisted efforts to increase ground-water pumpage because they were concerned that the aquifer would be depleted. However, information from the monitoring wells showed that pumpage could safely be increased. The water agency planned to continue monitoring these wells so that they will have baseline data before the onset of the next drought.
- **Kwajalein**—At Kwajalein Atoll, there was concern that the aquifer would not produce sufficient water of acceptable quality for the duration of the 1998 drought. The USGS resampled monitoring wells installed during a 1990-91 study and provided an updated assessment of ground-water resources. Additional appraisals could improve understanding of how the aquifer on Kwajalein responds to variations in pumpage and chloride.

- ***Other Atolls***—On several remote atolls, the USGS has conducted quick appraisals using surface geophysics (electromagnetic) and small-diameter driven well points, and additional appraisals. These contribute to a growing compendium of case examples of thin freshwater lens occurrence on small islands, and the dynamic response of such lenses to stresses such as pumping and droughts.

Information needs and deficiencies

The following information needs and deficiencies related to the issue of long-term ground-water availability on atolls of the Western Pacific were identified:

- ***Small-island appraisals***—Appraisals of the ground-water resources on the less-developed atolls are required to identify possible sources of drinking water during drought conditions. It is unlikely that these appraisals will be conducted unless the USGS takes a lead role in the effort to collect data necessary to estimate the extent of the fresh ground-water resources. These appraisals are needed to best evaluate the long-term availability of ground water on the less-developed atolls and the availability of ground water during drought.
- ***Resource management of developed islands***—On the developed islands, the main information need is related to resource management strategies that can be implemented to maintain low salinity of pumped ground water. Improved estimates of ground-water recharge are also important for estimating the long-term availability of ground water, and this requires improved estimates of evapotranspiration.
- ***Drought response***—On the less developed atolls, quick-response, water-management strategies for drought conditions must be identified and evaluated so that ground-water resources can be proactively managed. In addition, assessments of the ground-water resources on atolls can be made during drought conditions to enhance the understanding of the effects of climate variability on ground-water availability. Numerical ground-water flow models could be developed to optimize well distribution and pumping rates.
- ***Monitoring of ground-water resources***—Long-term monitoring of the ground-water resources on atolls will lead to a better understanding of the effects of climate variability on ground-water availability.

Water-quality related to land use

Background

The major water-quality issue on atolls in the Western Pacific is related to protecting drinking water supplies. Typically, land-use activities in areas of ground-water development have been limited to small single-family dwellings, coconut plantations, and domestic livestock and taro cultivation. Human and animal waste has the potential to infiltrate and contaminate the shallow ground-water lens, or directly contaminate open wells dug to the water table, which is typically less than 10 feet below the land surface.

Significant population growth and associated land-use changes have occurred on Majuro Atoll over the last two decades. The effects of present and future land-use practices on ground-water quality is a major concern because nearly all of the public water supplies during extended dry periods are derived from groundwater that is highly susceptible to contamination. Small-scale farms and animal feed lots have developed to help support the growing population. Fertilizers, pesticides, and animal waste products from these operations have the potential to contaminate ground water. Recent monitoring is limited to chloride and nitrate concentrations.

Current knowledge and USGS participation

The factors controlling relations between land-use practices and water-quality conditions on atoll islands are either poorly understood or unknown. To date, USGS water-quality programs on atoll islands in the Western Pacific have been limited to site-specific data-collection activities on the atolls of Kwajalein and Majuro. While data collection is necessary and important, there is a strong need is for programs that address water-quality issues from a broader aquifer perspective. In addition, there is a need to develop process-oriented studies to enhance the understanding of water-quality changes related to land use.

Information needs and deficiencies

Better information on the following topics could lead to improved quality of drinking water supplies on atoll islands. These topics are similar to those presented earlier for Hawaii, but are somewhat less complex given the smaller size, shallower water table, and hydrogeologic simplicity of atolls:

- ***Occurrence and distribution of water-quality conditions***—Ground-water studies are needed to describe relations among natural factors, human activities, and water-quality conditions. The goal of these studies is to help managers to evaluate long-term changes in water quality and implement effective water-quality management actions.
- ***Ground-water vulnerability assessments***—Assessments that show areas of greatest potential for ground-water contamination on the basis of hydrogeologic and anthropogenic factors are needed to protect drinking water supplies on Kwajalein and Majuro atolls. However, the soil, climatic, and chemical data that are needed for these assessments are extremely sparse and, therefore, contain considerable uncertainty. Model and data uncertainties must be incorporated into these assessments before GIS-generated ground-water vulnerability maps will be useful to regulatory decisionmaking. Furthermore, these models need to be statistically verified using water-quality data to provide a more technically defensible assessment.
- ***Occurrence and distribution of pathogens***—Ground-water resources on atolls are highly susceptible to contamination by pathogens. However, there has been little microbial sampling, and essentially no study of how microorganisms persist and are transported through atoll aquifers. As noted earlier, nearly all sampling has focused on microbial indicators, rather than direct measurement of pathogenic organisms. Studies of pathogenic

organisms could guide land-use and development practices and maintain the safety of drinking water supplies.

Climatic variability

Background

Atoll water supplies have extremely small storage capacities and are inextricably linked to climate variation. Hydrologic stresses and the limits to sustainable yield are inherently seasonal, and analyses based on average fluxes and stresses have much less utility than in larger systems.

Atoll water resources are strongly affected by climate variability at seasonal and interannual time scales. Rain catchment and storage is insufficient to carry most atolls through an entire dry season, even in a normal year, causing dry-season reliance on the secondary resource. Ground-water resources are similarly affected because of their small size. Atoll freshwater lenses are thin (about 10 to 60 feet) and contain only about 1 to 5 years worth of recharge in storage. An atoll freshwater lens has a much smaller storage buffer to smooth seasonal and interannual variability. Atoll lenses may expand and contract seasonally by as much as 20 percent, and the salinity of pumped water rises as dry-season saltwater intrusion progresses.

Under a highly variable and episodic rainfall regime, the fundamental challenge is to manage water resources in such a way to provide a sustainable supply throughout dry periods of little or no rain. This is usually accomplished through conjunctive use of rain catchment and ground water. Desalination is not extensively used owing to cost and a limited ability to maintain complex technologies in these remote locations.

Effects of the annual dry season are compounded occasionally by persistent drought. The most severe drought on record at Kwajalein lasted four years, raised salinity above drinking-water standards, and required temporary desalination. Interdecadal variation has been identified in some rainfall records, with the 1950's and 1970's being drier than the 1960's, 1980's, and 1990's. The wet conditions since the late 1970's are suggestive of a regime shift such as that associated with the Pacific Decadal Oscillation (PDO), or may reflect monotonic climate change associated with global warming.

The effect of drought on an atoll depends on the size of the resource and the duration and severity of drought. For example, small freshwater lenses may be taxed by even a normal dry season and intermediate-size lenses by a single dry year. Large lenses contain enough storage to ride out these short-term droughts, with pumped water rising to salinity limits only during the most severe multiyear droughts. It is notable that most of the 1998 drought-disaster effects in the Western Pacific atolls were basically failures of rain-catchment resources, and that the thick ground-water resources of Kwajalein and southern Majuro were comparatively little affected.

Current knowledge and USGS participation

During the most recent drought, the USGS was involved with several projects in the Marshall

Islands. A report documenting the effects of the drought on the major ground-water resource for Majuro is being prepared. USGS personnel installed a network of monitoring wells to estimate the size of the freshwater lens during and after the drought. The results were compared with a previous study done by the USGS more than a decade ago. This work was done cooperatively with the Republic of the Marshall Islands. In addition, the USGS acted in an advisory capacity for U.S. Army Kwajalein Atoll, and sampled ground water on Kwajalein Island during the last drought. Finally, the USGS acted as a technical resource for FEMA regarding some of the smaller atoll communities affected by the drought.

Information needs and deficiencies

Westernized atolls having centralized water-collection and distribution systems are most in need of programs to cope with droughts. Less-developed atoll villages are most in need of basic resource appraisals and assistance in developing ground-water supplies to mitigate drought effects.

Monitoring programs at Kwajalein and Majuro have collected pumpage and salinity data that reflect hydrologic responses to climate variation. A next step is to identify favorable water-management strategies, most likely through the combined use of linked ground water and optimization models. Statistical analyses of past climate would be needed to identify recurrence intervals for droughts of varying magnitude and to formulate scenarios for numeric simulation, including scenarios of climate variability and change.

Simulation or linked simulation-optimization could be used to identify best strategies for conjunctive use of catchment, ground water, and desalination; and for pumping from a complex assortment of wells having differing capacities and time-salinity responses. These are complex problems, and may need to be simplified to ensure practical solutions. Where numerical optimization is not feasible or warranted in scope, hydrologic monitoring and simpler analyses may be adequate to identify better management strategies, better well distributions, and whether more wells are needed to spread pumping more widely to keep salinity low.

Less-developed atolls can benefit from ground-water resource appraisals to identify whether a potable resource exists, whether it persists through droughts, and where it is best developed (usually where the freshwater lens is thickest, but also taking into account land-use factors). Atoll communities typically rely on ground water mainly for washing, and use it for drinking only as a last resort after rain catchment and coconut-milk supplies have run out. There is a compelling need to develop ground water as a resource to be used during extreme droughts. Although this role falls outside the USGS's mission, the USGS can provide scientific information to guide water development to mitigate drought effects.